FLEET TECHNOLOGY LIMITED

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ASSESSMENT OF HYDROGEN DAMAGE IN PETROCHEMICAL PROCESSING VESSELS

Final Report

by

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EXECUTIVE SUMMARY

The Metals Technology Laboratories is currently formulating research and development programs to be undertaken in the area of materials for production and processing in the petrochemical industry. To ensure that these programs are of benefit to the industry, its input was sought in the form of a questionnaire survey followed by in-person discussions with several industry representatives. The responses received are summarized in this report and based on these, subject areas recommended for CANMET initiative are:

i) Microstructure degradation - remaining life interrelationship; with a longer term perspective, activity in the area of application of fracture mechanics principles to engineering critical assessment in the creep range should also be initiated.

ii) Repair strategies for 2.25 Cr-1 Mo vessels (nozzle area, cracks in overlay) to avoid postweld heat treatment.

iii) Non-destructive evaluation of, and fracture behaviour due to HIC damage in hydrogen-charged C-Mn pressure vessel steels.

(This supplements the current CANMET initiative focusing on engineering critical assessment of planar flaws, perpendicular to plate surface, in hydrogen-charged steels.)

iv) Development of reliable, accurate and cost-effective NDE techniques, assuming it is within CANMET's mandate.

SOMMAIRE

Les Laboratoires de la Technologie des Métaux formulent couramment des programmes de recherches et développements à être entrepris dans le domains des matériaux pour la production et la transformation dans l'industrie pétrochimique. Pour s'assurer que ces programmes sont bénéfiques à l'industrie, un sondage sous forme de questionnaire suivi d'une discussion avec plusieurs représentants de l'industrie a été fait. Les reponses reçues sont résumées dans ce rapport et basé sur celles-ci, les sujets recommandés pour l'initiative de CANMET sont:

i) Relation entre la dégradation microstructurale - vie restante; avec une perspective à long terme, l'activité dans ce champs d'application des principles de la mécanique de la rupture et de l'evaluation critique de l'ingénierie au sujet du fluage devrait être aussi entrepris.

ii) Stratégie de réparation pour les réacteurs 2.25 Cr-1 Mo (région de l'ouverture, fissures dans les recouvrements) pour éviter les traitements thermiques après soudage.

iii) Evaluation non-destructive et comportement à la rupture dû aux dommages causés par l'hydrogène induit (HIC) dans les réservoirs sous pression en acier C-Mn chargés d'hydrogène.

(Ceci complète les initiatives courantes de CANMET qui sont concentrées à l'evaluation critique de l'ingénierie de défauts planaires, perpendiculaires à la surface de la plaque, dans un acier chargé d'hydrogène.)

iv) Développement de techniques d'END fiables, précises et rentables, assumant que c'est dans le mandat de CANMET.

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1.0 INTRODUCTION

In CANMET's PERD Program Task 5.1, "Materials for Production and Processing", several projects dealing with selection and fabrication of materials for pressure vessels in hydrogen service, and their life assessment and enhancement have been initiated. The focus of these projects has been 2.25 Cr-1 Mo steel pressure vessels and components operating at elevated temperatures, or C-Mn pressure vessels operating in a wet hydrogen sulphide (H_2S) environment, and these include:

- Narrow gap welding of thick 2.25 Cr-1 Mo vessels (for hydrocracker application in refineries);
- Disbonding resistant procedures for stainless steel weld overlaying of 2.25 Cr-1 Mo steel (for hydrocracker application);
- Repair procedures (without postweld heat treatment) for Cr-Mo pressure components;
- Engineering critical assessment (ECA) of a service-damaged vessel (fabricated from A516 Gr 70 steel);
- Evaluation of the resistance of C-Mn pressure vessel steels to hydrogen-induced cracking (HIC), stress-oriented hydrogen-induced cracking (SOHIC) and sulphide stress cracking (SSC).

At this time, CANMET is planning the direction for future research and development efforts. However, before initiating projects in this area, CANMET wished to obtain input from the Canadian petrochemical industry so that any programs initiated would be of direct relevance to the industry needs, and therefore would merit its financial support.

2.0 OBJECTIVE

Fleet Technology Limited was given the assignment to consult with the industry with the objectives to:

i) identify hydrogen-induced damage in relation to pressure vessel operating condition (i.e., creep and hydrogen damage in heavy wall 2.25 Cr-1 Mo vessels overlayed with stainless steel), and occurrence of HIC, SOHIC and SSC in lower temperature vessels);

ii) identify requirements for non-destructive testing methodologies for assessment of the location and size of damaged regions;

iii) evaluation of materials for optimizing resistance to hydrogen-induced damage,

iv) identify the need for techniques for estimating the residual life of pressure vessels containing hydrogen-induced damage,

v) define research and development initiatives to assess and control hydrogen-induced damage in pressure vessels and components.

3.0 APPROACH

The approach followed in this project comprised three stages:

i) A brief review of the literature to aid the formulation of a questionnaire for the industry;

ii) assessing questionnaire responses from the industry and interviewing staff in selected organizations;

iii) analyzing the responses and preparing the report.

4.0 FINDINGS

4.1 LITERATURE REVIEW

For the purposes of this review, the literature can be divided into two categories, dealing with 2.25 Cr-1 Mo vessels (high temperature-high pressure hydrogen) and C-Mn steel vessels (subject to wet hydrogen sulphide environments), respectively.

2.25 Cr-1 Mo Vessels

The literature on 2.25 Cr-1 Mo steels dates back to at least the early 60's. Most research work in the 60's and 70's was carried out in the U.S.A. and dealt with stress rupture characteristics of the steel (1) and weld metals deposited by the shielded metal arc and submerged arc welding process. This was followed by studies on temper embrittlement behaviour of the steels, and formulation of the X and J factors to quantify the role of alloying elements (Mn and Si) and impurities (P, As, Sb, Bi, etc.) in causing temper embrittlement.

By the late seventies, companies in Japan, mainly Japan Steel Works, had developed steel-making practices and welding consumables that would easily enable the steel and weld metal to meet 40 J @ -40°C Charpy V-Notch requirement, even after temper embrittlement induced by a controlled step cooling treatment.

In the early 80's, the focus shifted to the investigation of disbonding between the overlay and 2.25 Cr-1 Mo substrate, caused by hydrogen build-up at the interface, especially during fast cool downs. Since then, several studies have tried to identify the factors that promote its incidence, and developed and optimized welding procedures that enhance disbonding resistance (2).

In recent years, there has also been a significant development effort, in Japan and the U.S.A., to develop modified 2.25 Cr-1 Mo and 3 Cr-1 Mo steels that would enable vessels to be operated at higher temperatures. Thus, according to the Nelson diagram, 2.25 Cr-1 Mo steel has been used safely without hydrogen attack at temperatures up to 455°C (850°F). The modified steels (with vanadium) are believed to be acceptable to 482°C (900°F), at least on the basis of stress-rupture tests. For reliable application of such steels in high pressure hydrogen environment, there seems to be a need for further work in evaluating their resistance to hydrogen attack at high temperatures, especially when the steel is also under stress. Finally, there has been increased interest in extending the application of fracture mechanics to the high temperature regime, since weld repairs can be rather expensive, especially if a subsequent postweld heat treatment is needed.

Some of these subjects were covered in a conference held in Paris in 1989 (3). The areas for further research effort were identified at this conference to be:

- The effect of hydrogen on creep behaviour (creep rate; creep ductility; nucleation, growth and coalescence of methane bubble;
- effect of residual stresses on creep behaviour
- evaluation of new materials.

Since the conference in 1989, several Industry-Materials Properties Council-American Petroleum Institute-sponsored projects have been initiated in this area, and though their details are not in the public domain, their capsule statements as given in an MPC Liaison Report to API (October 1991) are as follows:

- MPC continues its successful study of the technology of advanced materials for hydrogen pressure vessel service. This work has resulted in Code acceptance of a new grade of 2.25 Cr-1 Mo steel. Tests of susceptibility to hydrogen embrittlement and hydrogen attack are continuing. A report of hydrogen embrittlement mechanisms has been prepared. New test methods are being developed due to MPC's intervention in this area.
- A Fitness-for-Service methodology is being developed for heavy wall vessels for hydrogen service.

- A high-strength hydrogen-resistant vanadium containing 2.25 Cr-1 Mo steel has been qualified for ASME Code service to 900°F (482°C). This allows application in welded construction under ASME Division 2 rules. Weldments have been studied in detail. Testing under 3000 psi (20685 kPa) hydrogen has justified positioning of this material on the Nelson Curve above ordinary 3 Cr steels. Tests of base metal have exceeded 30,000 hours at 950°F (510°C). A proposal has been made for inclusion in API 941. A Code Case for BS5500 has been prepared.

- MPC has a very active program to study hydrogen attack resistance of 2.25 Cr-1 Mo steel. Many studies of weldments are in progress and several have exceeded 20,000 hours of stressed exposure. A program to incorporate these results in the evaluation of high temperature fitness-for-service of hydrogen vessels is under way. *Hydrogen attack appears under stress at 825°F (440°C).*

- A program is in progress to provide guidance for prevention and repair of cracking of 1.25 Cr-0.5 Mo-Si and 1 Cr-0.5 Mo pressure vessels and piping. Problems are more widespread than originally thought. A preliminary report was prepared with API support. API support in 1991 and 1992 is anticipated for the program. Crack prone heats have been identified.

- MPC's Project Omega, on remaining life evaluation of process equipment in elevated temperature (creep) service has been used in evaluating petroleum industry components. Many petroleum companies have joined the twenty-two-company consortium to support and guide this work. It involves carbon steel, several chrome-moly steels and has recently been expanded to include stainless steels. Guidelines for life assessment are being written and a new methodology for testing has been developed. A needed database is being established.

- MPC is running stress rupture tests on chrome-moly weldments for steam and process piping service. Service type failures have been simulated in the laboratory.

Vessels in Sour Gas Service

Vessels have been designed and fabricated to operate in sour gas environments for more than 40 years now. Very early on, it was appreciated that in wet sour environments, hydrogen charging can occur into the steel causing the problems of hydrogen embrittlement, sulphide stress cracking (SSC) and blister formation at non-metallic inclusions or laminations.

Such vessels are traditionally fabricated from relatively low strength C-Mn steels

Such vessels are traditionally fabricated from relatively low strength C-Mn steels (such as A516 Gr 70) which have been believed to be affected only marginally by hydrogen embrittlement. Further, blisters, being in a plane parallel to the shell plate surface, were considered incapable of causing "through-thickness" cracks. They could affect the strength due to local reduction in wall thickness, and therefore suitable actions such as weld repair, metallic liners etc., were undertaken at appropriate times.

The focus of research endeavours in the 60's therefore was the prevention of sulphide stress corrosion cracking (or stress corrosion cracking in the presence of other species such as cyanides in the process stream). This culminated in the NACE Standard RP-04-72 which places limits on steel's hardness in order to minimize the susceptibility to sulphide stress cracking. The same hardness limit was transferred to welds and heat-affected zone in order to make weldments also resistant to sulphide stress cracking.

During the 70's, the evaluation of line pipe steels in wet H_2S environments showed that the blister formation at inclusions could also be accompanied by cracks linking them, and this came to be known as step-wise cracking (the formation of blisters and step-wise cracks are now together termed as hydrogen-induced cracking (HIC)). Alloying of the steels with elements such as Cu, reduction in inclusion content and their shape control, and enhancement of the overall toughness of the steel were the approaches used to produce a new generation of line pipe steels that would be resistant to HIC.

The catastrophic failure of a monoethanolamine (MEA) absorber vessel in 1984 sensitized the pressure vessel operators to the possibility of severe HIC problems in pressure vessels also and to the need for a more sensitive non-destructive inspection technique. Inspection of numerous such vessels in the next few years using the wet fluorescent magnetic particle inspection technique revealed (4) that:

i) ≈ 30% of the vessels inspected had cracks, two-thirds of these being deeper than the corrosion allowance;

ii) ≈ 20% of the postweld heat-treated vessels also had cracks.

A vast majority of these cracks were associated with welds.

The key issues for further research to address the HIC issue were identified in 1989 (3) to be:

- The effect of the sour environment on crack growth rate;
- the effect of hydrogen present in steel on its fracture toughness

- identification of a threshold stress intensity factor, below which cracks would not grow.

It should be noted that all of the above are in the context of sulphide stress cracks, present usually in the weld zone and oriented perpendicular to the hoop or the longitudinal stress. Blisters and step-wise cracks are oriented essentially parallel to the principal stresses and are not easily treated using fracture mechanics principles.

Since the time of the conference in 1989, certain MPC-API-Industry-sponsored projects have been initiated in the U.S., and they are briefly mentioned below:

- MPC has started a program on Fitness-for-Service Analysis, Evaluation and Inspection Methodologies for Equipment Subject to Aggressive Service Conditions. More than 25 petroleum, chemical and engineering companies have joined to support this activity. This program will provide the technical basis for decisions and methods used for assessment of degradation and flaws and wall thinning. Some of the technology developed will be used to enhance future API and other inspection Codes. A draft report on method has been prepared under Phase I.

- A program on hydrogen-induced cracking is in progress. It deals with evaluating materials and welding procedures for petroleum industry process vessels and the development of test methods. Most of the major petroleum companies have joined the consortium supporting this project. In addition, steelmakers and fabricators are financing part of the program. A test procedure is being refined. The effects of different environments and welding are being studied.

- MPC has started a program to demonstrate by actual test the crack propagation and fracture behaviour of steels used to contain aqueous hydrogen charging solutions. NDE is heavily emphasized. API support has been provided.

- MPC is collecting samples of components with flaws which can be used to calibrate or verify NDE capabilities. These materials are archived by MPC. This activity is related to MPC's demonstration project on fitness-for-service for heavy wall vessels. MPC has prepared an ultrasonic test qualification block of clad, welded, thick-walled chrome-moly steel. It is situated at a petroleum company refinery and may be used for procedure and personnel qualifications.

4.2 QUESTIONNAIRE AND INTERVIEW RESPONSES

Based on the brief literature review, the key questions that needed to be addressed were considered to be:

i) What is the incidence of damage in the vessels of interests?

ii) Does the industry feel the need for research and development work to enhance the life of existing vessels, assuming they have accumulated some damage or to focus on prevention or minimization of hydrogen-induced problems in new constructions;

iii) If it is the life enhancement of existing vessels, then which specific areas would yield the greatest benefit? (Non-destructive inspection techniques, engineering critical assessment and estimation of remaining life; welding repair technology.)

The questionnaire that was prepared is included in Appendix A. It was sent to twenty-two persons in organizations listed in Appendix B. Responses, in writing or in the form of in-person discussions, were received from 15 of these.

The responses to various questions are summarized in the following sections.

4.2.1 Heavy Wall 2.25 Cr-1 Mo Vessels Overlayed with Stainless Steel

A. General

The companies involved in the operation of such vessels include Shell Canada, Petro Canada, Imperial Oil, Syncrude, Suncor, and Husky Oil. It is estimated in all, there are about 35 such vessels operating in Canada and that half of these are about 20 years or older, and mostly fabricated within North America. The recent ones, less than 15 years old, have been mostly fabricated in Japan. The two most recent vessels of this type for Husky Oil were also fabricated in Japan and the base material is a 3 Cr-1 Mo-V-B steel. However, these vessels are not in operation yet. The maximum thickness of these vessels is ≈ 225 mm.

B. NDE and Incidence of Flaws

Most companies inspect the vessels at approximately two-year intervals. This may involve a complete shut-down and wet fluorescent magnetic particle inspection (WFMPI) from the inside, followed by ultrasonic examination (UT) if needed. Others may use UT from the outside and internal examination at alternate inspections. These techniques may be supplemented by acoustic emission during the cooling for shutdown to identify

regions of high acoustic activity, and therefore of possible flaws, to be examined more carefully by subsequent WFMPI or UT.

All the companies having such vessels in operation indicated that the incidence of service-induced planar flaws in the 2.25 Cr-1 Mo substrate to be negligibly small. The planar flaws detected are usually confined to the overlay only and attributed to design considerations, i.e., stress concentrations inducing thermal fatigue type of cracks. Structurally, they don't represent a major risk.

This is not entirely unexpected since most vessels have a design temperature of 455°C (850°F) but are operated at temperatures in the range of 343° to 427°C (650°F to 800°F), well below the Nelson Curve Limit. It is understood that even though the new 3 Cr-1 Mo-V-B steel vessels at Husky have a design temperature of 510°C (950°F), they will be operated at no more than 482°C (900°F) (ASME Code Case 61). The MPC report referred to earlier indicated that hydrogen damage has been seen in the laboratory in 2.25 Cr-1 Mo steels at temperatures below 825°F (440°C). However, it is not clear how high the stress was, and if the sample was overlayed with stainless steel or not.

It is frequently mentioned that Cr-Mo equipment has a fairly high incidence of cracks in them. However, these observations are generally in relation to 1.25 Cr-0.5 Mo steel vessels which have significantly lower hydrogen partial pressures, and do not have a stainless steel overlay. The cracking has been attributed to creep embrittlement.

Notwithstanding the infrequency of cracks in the substrate in heavy wall stainless steel overlayed vessels, all the companies seem constantly watchful of the presence of flaws in the pressure boundary, and therefore in general, there was a great interest in accurate but less expensive non-destructive examination techniques to assess damage.

Some of the companies have tried the Time of Flight Diffraction (TOFD) method to accurately size flaws when they were suspected to be present, but only with a mixed degree of success. In one instance, an approximately 12 mm deep-buried flaw was indicated by TOFD but was actually found to be only 3 to 4 mm deep. In any case, it was felt that conventional ultrasonic techniques tended to be inaccurate and quite operator-dependent, and the TOFD technique, while successful in certain instances, is too expensive and needs contractors from outside the country. And the acoustic emission technique is really used as a screening device, i.e., AE activity may indicate the presence of a flaw; but absence of AE activity doesn't necessarily mean that no flaws are present.

During the in-person discussion, it also became evident that even though the incidence of planar flaws in the Cr-Mo substrates is infrequent, there is still some concern with the possible long term effect of temperature and hydrogen on microstructure, and on temper embrittlement. While in the latter case, there are substantial data in literature relating composition and impurities (As, Sn, etc.) to

potential for temper embrittlement, it was felt that non-destructive or semi-non-destructive (small specimen volume) techniques to assess microstructural damage and temper embrittlement would be of help.

As indicated earlier, in addition to the various petrochemical companies, discussions were also held with Ontario Hydro. The thick Cr-Mo steels employed in steam generating equipment (2.25 Cr-1 Mo; 1.25 Cr-.5 Mo; 0.5 Cr-0.5 Mo-0.25 V) are not overlayed with stainless steel; the operating temperature is higher (≈ 540°C) and there is no hydrogen in the environment. Incidences of creep cracks in fine grain or intercritical HAZ have been reported in these applications and there are significant efforts underway at Ontario Hydro to assess:

- The remaining life, based on microstructural damage, before the appearance of cracks,
- non-destructive techniques to assess microstructural degradation, and
- non-destructive techniques to accurately size flaws. It was felt that in this context, techniques based on radiography and used in the aerospace and medical industries could be a guide (radiography tomography, for example).

C. Engineering Critical Assessment

Since planar flaws have been so rare in the 2.25 Cr-1 Mo substrate, the need for ECA has also been rare. All the companies are familiar with ECA's carried out for brittle fracture, and if a crack were to be detected today, such an exercise is likely to be carried out. This success of the ECA for brittle fracture would depend on the accurate knowledge of the material toughness. Generally, lower bound toughness will be assumed, and that in conjunction with the potential inaccuracies in flaw size measurement means that invariably the flaw will need to be repaired. The only advantage of the ECA exercise would be to allow continued operation of the vessel for a limited length of time, perhaps till a scheduled shut-down, in case the flaw is found to be smaller than the critical size.

As far as ECA from the point of view of creep crack growth is concerned, its general need is not established yet, at least from the point of view of the existing 2.25 Cr-1 Mo overlayed vessels. Its application would be more meaningful for steam generation equipment. However, Ontario Hydro felt that creep damage phenomenon (degradation kinetics; microstructural changes, etc.) need to be understood well before fracture mechanics concepts can be used for assessment of flaws at high temperature.

D. Weld Repair

Once again, due to the relative infrequency of the cracks in the substrate, weld repair has not been a major issue. On a few occasions when repairs have been needed, adequate preheat and local postweld heat treatment were applied to conform to the code requirements.

As was mentioned earlier, cracking in the weld overlay or disbonding, can be relatively more frequent. Such repairs were generally considered to be straight forward, and if these required welding on to the Cr-Mo substrate, then preheat and postweld heat treatment are incorporated into the welding procedures. For more recent vessels fabricated in Japan, the fabricator is understood to provide a significant amount of technical back-up in terms of adequate welding repair procedures.

Also, during the last 10 years or so, a fair amount of research effort has been devoted to develop disbonding-resistant welding and suitable operational procedures, and it was felt that in new constructions, disbonding-related problems will be negligibly small.

E. New Heavy Wall, Stainless Steel Overlayed Cr-Mo Vessels in the Future

It was agreed by virtually all the companies that any new vessels built will be from recently-developed steels (3 Cr-1 Mo or 2.25 Cr-1 Mo steels modified with V, Ti, B, etc.). However, except for one organization, the general consensus was that no such vessels will be built for Canadian organizations over the next five years.

Notwithstanding the above, all respondents felt investigations should continue to better characterize the advanced steels and their weldments, especially from the point of view of in-service performance. It was apparent at the same time that sentiment was an expression of an ideal situation, and that in the current state of the economy, the companies would be hard-pressed to devote financial and other resources to investigate the advanced materials when no new equipment of this type if being planned.

F. Areas for Research and Development at Present

In the questionnaire, the companies were asked to prioritize eight subject areas for further research, and the responses are quantified in Table 1 by assigning points as follows:

Priority	Points
1	10
2	8
3	6
4	5
5	4
6	3
7	2
8	1

When clear priorities were not stated, the points were divided equally between the areas deemed important by the respondent.

It is clear that the only subject area for which there is a semblance of consensus regarding need for further work is '**non-destructive examination**'. The main objectives for further work, based on various comments should be :

i) To develop the ability, within Canada, to perform NDE from outside, while the vessel is in operation;

ii) to improve the accuracy and consistency of the results obtained regarding flaw sizes, without rendering the technique prohibitively expensive.

The second most commonly mentioned subject area for research and development, was **relating microstructure to accumulated damage, and the remaining life**. This may seem a bit surprising since the overlayed 2.25 Cr-1 Mo vessels in practice operate below the creep range, and there is little evidence of microstructural degradation and damage accumulation in these steels. Detailed discussions indicated that there were **two slightly different objectives** that the respondents had for this research and development area, these being:

i) NDE technique to assess damage and remaining life, presumably when the vessels are near or beyond the end of their design life;

ii) to estimate mechanical properties, especially fracture toughness, from microstructure (and hardness and composition) thus obviating the need for

Table 1: Research and Development Priorities for 2.25 Cr-1 Mo Vessels

Subject Area for Research	Current Owner/Designer								Average	Other		Final Average
	1	2	3	4	5	6	7	8		9	10	
1. H_2 on Creep Behaviour	9	2	-	6			2	6	3.10	N.A.	4	3.20
2. H_2 on Low Temperature Toughness	3.5	3	-	5	**	6	3	6	3.30	N.A.	10	4.05
3. Temper Embrittlement	2	1	-	4	**	6	1		1.75	5	5	2.40
4. Repair without PWHT (Nozzles, etc.)	3.5	10	-		**	6	10		3.70	6	8	4.35
5. Repair Overlay without PWHT	9	8	-		**		8	6	3.90	N.A.	3	3.80
6. ECA - creep	5.5	4	-			6	4		2.40	4	*	2.60
7. NDE	5.5	5	-	9	10	10	5	10	6.80	9	6	6.95
8. Microstructure - creep	1	6	-	9	8		6	6	4.50	9	*	5.00

N.A. Not applicable

* For high temperature furnace tube applications

** Assistance expected from fabricator/supplier

extracting large samples from the vessel, or for using lower bound values for mechanical properties based on data in literature.

The **most common application for the first subobjective** above was however found, in discussions, to be **heater tubes in steam generators, reformers, pyrolyses furnaces, etc**. Various different types of alloys - Cr-Mo (2.25 Cr-1 Mo, 5 Cr-0.5 Mo, 9 Cr-1 Mo), austenitic stainless steels (310, 316, 321), higher carbon cast austenitic stainless steels and nickel-based (800 H, for example) - are used for these applications, depending on the temperature range in which they operate. Individual petrochemical companies have several such furnaces, and each furnace has hundreds of such tubes. Further, depending on their location and contents, their failure can lead to fires and fatalities.

There are numerous factors which lead to unexpected failure of these tubes, e.g., tube temperatures exceeding design temperature, fouling, oxidation and corrosion, carburizing, etc. In-situ microstructure examination of selected tubes or even short-term destructive examination of selected tubes at scheduled shut-downs to assess remaining life would be of great use to the petrochemical industry.

It is understood that there is a semi-empirical approach available which, based on operational history and inspection results enables one to infer the remaining life; however, it is obviously not completely successful and further work is needed. Organizations in Europe and in the U.S.A. (EPRI, SWRI) are believed to be active in the area; the investigators apparently focus on modelling of stresses, microstructure-remaining life correlation, ultrasonic attenuation-microstructure degradation relationship etc.

The **third important area** for further research and development is seen to be the **development welding procedures that could obviate the need for a subsequent postweld heat treatment**, notwithstanding the fact that cracks in the 2.25 Cr-1 Mo substrate are rarely observed. The current program underway at CANMET in collaboration with Ontario Hydro and Novacor is obviously a significant first step in this direction. However, the work to date apparently focuses on large surface area repairs, and it was suggested that there is a need to modify or adapt these for applications where the geometries may be more constrained, e.g., nozzles. The second aspect is that repairs of the stainless steel overlay are relatively more frequent, and if these repairs can be implemented without the need to postweld heat-treat on account of welding on to the substrate, then there could be significant cost savings. However, some respondents did feel that avoidance of postweld heat treatment would be a high risk research project requiring long term studies to demonstrate their adequacies. In contrast to these concerns, it was pointed out by others that mechanical damage to the overlay alone can be addressed by flame or arc spraying stainless steel, and in the case of crack-like damage, stainless steel patch plates can be welded.

All the three areas defined above are in the context of existing vessels, where the in-service problems are small in magnitude, assuming that the current NDE practises are adequate to detect the flaws that may be present.

If focus is shifted to fabrication and operation of **vessels in the future**, even though that may be hard to do in the current economics climate, it was felt that there is merit is devoting effort to **develop fracture mechanics methodologies to assess significance of flaws at high temperatures (i.e., in the creep range)**. Current practice of operating at ≈ 30°C below the design temperature is uneconomic from the point of process efficiency and if the new generation of vessels are to be operated at the design temperature, then it is only prudent to have flaw assessment methodology available should it lead to some flaws in service. Although weldability and repairability of the new generation of steels could be another area warranting study, the primary effort in this area is being devoted by the Japanese fabricators and by the U.S. based petrochemical companies in conjunction with MPC.

One **last area for investigation**, mentioned by two of the respondents was **sulphidation of vessels at elevated temperatures**. Instead of expected scale formation and corrosion with a declining rate, local penetration has been observed when operating temperatures are near 370°C (700°F). Some oxygen-containing cracks have also been observed at 482°C (900°F) operating temperature, and it was felt that understanding of this phenomenon would be a help.

4.2.2 Pressure Vessels for Sour Service Environments

A. General

Most of the companies that responded to the questionnaire have vessels or other equipment that operate in wet sour service. Companies like Mobil Canada and Amerada Hess Canada, own and operate sour gas processing plants and have hundreds of vessels in severe sour service, and all of these are postweld heat-treated, primarily to avoid sulphide stress cracking. The oil refineries usually have smaller number of such vessels (20 to 50, typically) and these are generally postweld heat-treated only if the ASME code requires, i.e. the thickness is greater than 38 mm. The steels involved are C-Mn hot-rolled or normalized, and have been purchased to specifications such as ASTM 285, A212, A516 Gr 70 etc. Hydrogen damage in one form or another, and to varying degrees has been observed in these vessels. The hydrogen damage can take the following forms:

(a) Planar cracks at weld toes.

These have been observed in both as-welded and postweld heat-treated vessels, and are attributed to one or more of the following:

- initial fabrication flaw, usually shallow, detected by a more sensitive inspection technique;

- thermal fatigue;

- sulphide stress corrosion cracking when the hardness requirement of NACE Standard MR 0175-91 "Sulphide Stress Cracking Resistant Metallic Materials for Oilfield Equipment" is not met. In postweld heat-treated vessels, SSC may occur due to the presence of residual elements in steel so that at the standard PWHT temperature (620°C, 1150°F), the hardness does not decrease to a value below HRC 22 or its equivalent. A second possible reason is that sometimes attachment welds may be made without a subsequent postweld heat treatment.

(b) Blisters and step-wise cracking (Hydrogen-induced cracking)

Blisters have been observed in both as-welded and postweld heat-treated vessels. The blisters are usually located between the midwall and internal surface, and can break open in service at the internal surface if there is sufficient hydrogen pressure built up inside. The blisters may be accompanied by step-wise cracks; however, unlike pipeline steels, step-wise cracks emerge infrequently at the surface in pressure vessels, and it has not been a common practise in Canada to perform metallography to ascertain if step-wise cracking is also present with the blisters.

B. HIC-Resistant Steels

HIC-resistant steels are very clean steels (low oxygen and sulphur, and therefore low inclusion count), frequently incorporating a vacuum degassing treatment also. The carbon equivalent is also limited to control weldability and susceptibility to sulphide stress cracking.

Some of the companies have employed HIC-resistant steels in the past for vessels in sour service. However, due to the limited length of experience (5 years or less), there is no definitive conclusion regarding their immunity from HIC, since in rather severe quality assurance types of tests, SOHIC damage has been observed in these steels.

Secondly, when the steel tonnage required to fabricate a vessel is relatively small, it can be difficult to procure HIC-resistant steels in time. Some organizations have tried to overcome this problem by having an intermediate level of specification, i.e., controlling carbon equivalent and inclusion rating (e.g. ASTM E45). The latter usually means that vacuum degassing is no longer mandatory and sulphur levels may be typically 0.01 wt% maximum instead of the usual limit

for HIC-resistant steels which may be 5 or 10 times smaller. However, the limited experience with such specifications has been mixed - some meeting success, and not others.

There is currently an MPC program underway at Cortest Laboratories which is nearing completion and has the specific objective of relating sour service environment severity to the incidence of HIC damage in A516 Gr 70 steels produced using different steelmaking practices (hot-rolled, normalized, inclusions shape and content, vacuum degassing, etc.). It is hoped that this study will shed more light on the adequacy of HIC-resistant steels in various environments.

C. Preventing HIC Damage in New Vessels

The strategy to guard against HIC damage seems to depend on the company and its past experience.

It seems that oil refineries, generally speaking, opt for HIC-resistant steels, and incorporate PWHT only if code requires it. In the sour gas processing plants, PWHT is considered a must to avoid sulphide stress cracking and the use of HIC-resistant steels would depend on schedule and cost constraints. Barrier layer (coating or lining, or clad steel) is another option available, and stainless steel clad would be ideal to eliminate HIC damage, especially in situations where, due to internal attachments etc., inspection and repair would be difficult. However, the clad steel option is considered too expensive for new vessels, and the preference is to apply coatings (epoxy, aluminum spray, other flame-sprayed coatings, etc.) during a scheduled shut-down if HIC damage is discovered. All the same, there were a couple of companies who would consider coatings in new vessels. The hesitation on the part of others to rely on coatings stems from factors such as:

i) Application of coatings, especially flame-sprayed, is difficult in small vessels (can get too hot inside),

ii) permeability and holidays in coatings may accentuate the corrosion,

iii) the maintenance of coatings can be a nuisance, and coatings and liners may make in-service inspection more difficult.

D. Addressing HIC Damage in Existing Vessels

As mentioned before, HIC damage has been observed by all the responding companies having vessels in sour service. It is detected by visual inspection and wet fluorescent magnetic particle inspection of the internal surface at scheduled shut-downs. Occasionally, ultrasonic inspection from the outside surface is also carried out prior to the shut-down to identify areas which need to be inspected more thoroughly from

inside. To further characterize flaws, (planar and step-wise cracking) advanced ultrasonic techniques have been used, but with mixed success. A brief summary of the experiences is given below:

(a) In one organization, straight beam ultrasonic inspection revealed several midwall reflectors, and it was inferred that step-wise cracking was present; metallographic examination after removal didn't reveal any HIC damage;

(b) Shear wave ultrasonic examination has been used in another organization to define the extremities of step-wise cracks.

(c) One organization has tried TOFD, P-Scan and C-Scan technique to size HIC damage. It was concluded that TOFD was successful 2 out of 3 instances to recognize step-wise cracking; P-Scan tended to oversize the flaw and the C-Scan approach was the least successful.

(d) In contrast, one company has found C-Scan to be the most suited for delineating step-wise cracking.

Clearly, even though some of the advanced ultrasonic inspection techniques are automated, there is no reliable evidence of the accuracy and consistency of results obtained by these techniques, and of one technique being superior to the others.

Once the non-destructive examination has been performed to delineate the flaw, the information obtained can be used for engineering critical assessment or for formulating a repair strategy.

At this stage, most companies are familiar with the application of ECA methodologies for planar flaws, and current effort is to simplify the schemes so that it can be implemented at the plant level. ECA approaches for HIC damage (blisters and step-wise cracking) are in their infancy.

One organization treats isolated blisters as cracks of length equal to the diameter of the blister and depth equal to the planar location of the blister from the internal surface. This is obviously extremely conservative.

Another organization has developed an in-house approach which treats the blister as penny-shaped flaw with stresses in the through-thickness direction due to the internal pressure of the hydrogen in the blister. However, these analyses are for a single blister, and if multiple blisters in close proximity and perhaps in different planes are present, then it is not clear how these will be treated.

Another concern is that when multiple blisters are present in the bottom courses of towers and tall vessels, the buckling strength may be compromised. This area however, seems to have been adequately addressed by internal company guidelines based on strength of materials considerations.

In practice, fracture mechanics-based engineering critical assessment, especially for HIC damage, is rarely employed and the general approach is to monitor the damage and repair it where needed. HIC damage manifests itself as blisters to begin with. If they are isolated and small, they are usually located close to the surface and can be ground away without reducing the thickness beyond the corrosion allowance. However, if the blisters are large ($\approx$ 20 cm^2 or larger), or ruptured, then they are weld repaired.

Weld repairs always involve a bake-out to drive away the diffusible hydrogen, and thus to reduce the propensity to cold cracking in the weld metal or the HAZ. In addition, a postweld heat treatment or a temper bead technique may be used, depending on the perceived severity of the environment.

The experience with weld repairs seems to have been mixed also. Some organizations claimed the repairs to be complete successes. Others indicated three main problems:

- Formation of additional blisters and cracks during preheating and welding for repair;
- formation of additional blisters due to postweld heat treatment;
- recurrence of the blisters after one to two years of service.

It should be added that the consensus emerging from the NACE's Working Group T8-16D (Rev. 4, June 1991) on "Repair of Carbon Steel Pressure Vessels Damaged in Wet H_2S Service" reflects reluctance in repair welding of HIC damage. The consensus on repair strategy can be summarized as follows:

Planar Flaws at Welds	Blisters or Step-wise Cracks	Repair Approach
No	Yes	Monitor or Barrier Layer.
Yes	No	Grind (< corrosion allowance).
Yes	Yes	Monitor and ECA. Replace.

The consensus in this document therefore seems to be that HIC damage (blisters or step-wise cracks) should not be weld repaired, and the preferred approach to control its incidence is the provision of barrier layers (strip lining, weld overlay, organic or inorganic coating).

Finally, it should be added that an entirely different approach is being used by one organization to control the incidence of HIC damage in vessels. This is to install hydrogen probes on the vessel walls, and then to monitor the hydrogen flux. It is understood that the company can control the process (temperature, process stream chemistry, etc.) to ensure that hydrogen flux doesn't exceed a certain predetermined threshold level. The threshold level may be different for different steels, and would need to be established, based on tests that involve hydrogen permeability - HIC damage measurements and correlations.

E. Areas for Further Research and Development

In the questionnaire, five subject areas were mentioned as candidates for further research and development, and the respondents were asked to prioritize these. One additional subject area (the effect of hydrogen on fracture toughness) was added afterwards as it came up during the discussions. The results of this exercise, following the same scheme as for high temperature vessels, are summarized in Table 2.

The **development of cost-effective NDE techniques** to accurately define the HIC damage from the O.D. surface is overall **the highest priority for most respondents**. The technique should not only accurately size planar flaws perpendicular to the surface, but also distinguish step-wise cracking from inclusion clusters, laminations, etc. While most respondents think of developments in ultrasonic testing to achieve this goal, developments in radiography in medical and aeronautical fields (tomography) may also be appropriate for the subject application. The availability of such techniques is useful for:

- assessing if flaw growth is occurring in service;
- performing ECA;
- for developing repair strategy.

The **second highest priority** was accorded to establishing the **effect of hydrogen on steel's toughness**. Such information is not only an extremely important input for a rigorous engineering critical assessment, be it for HIC damage or for planar flaws perpendicular to the surface, but may also have a bearing on the perceived benign nature of minor indications. There are two investigations at least wherein the presence of electrolytically-charged hydrogen has been shown to bring down the fracture toughness of ferritic-pearlitic steels to more or less one common low value (for example,

Table 2: Research and Development Priorities for Pressure Vessels with HIC Damage

Subject Area	Respondent - Refinery									Sour Gas Plant		Avg.	Respondent - Others				Avg.
	1	2	3	4	5	6	7	8	9	10	11		12	13	14	15	
1. NDE of HIC Damage	10	6	7	10	8	8	10	10	8	9	10	8.7	8	9	10	5	8.5
2. ECA of HIC Damage	6	5	5		6	10	8		8	9	6	5.7	8	9	6	4	6.0
3. Weld Repair		8	10	8			6					2.9		6	8	6	3.5
4. H_2 Probes		10	4	6		5.5	5					2.8				10	2.7
5. Barrier Layer	8	4	7	5	10			6				2.7		4.5		8	3.5
6. Effect of H_2 on Fracture Toughness	5	-	-	-	5	5.5	-	8	8	6	8	6.5	8	4.5	-	-	6.4

see Reference 5). However, more data are needed to establish the influence of more realistic levels of hydrogen content, and for a larger variety of steels.

The **third most important** area for further research and development is deemed to be the **development of methodology for engineering critical assessment of HIC** damage (blisters and step-wise cracking) as apart from planar flaws perpendicular to the surface. However, in assessing the success of future programs in this field, it is noted that:

- One should have an accurate NDE technique available to size the flaws;
- one should have a comprehensive knowledge of the material properties (i.e., the effect of hydrogen on fracture toughness);
- for ECA to be effective, it should incorporate flaw growth in service so that inspection intervals can be prolonged;
- in practice, if HIC damage is seen, the tendency is to repair it if at all possible; ECA is used as an option of last resort when other alternatives (repair, etc.) cannot be scheduled or affected areas are inaccessible;
- the flaw planes are parallel to principal stresses, and such a situation is not readily addressed by fracture mechanics.

Overall, while the desirability of having an effective ECA approach for HIC damage was expressed, there were also reservations if some of the hurdles mentioned above can be surmounted without spending an unacceptably large amount of financial and technical resources to it.

At the same time, it is intuitively felt that step-wise cracking, and especially blisters are not as injurious as flaws perpendicular to the surface, and some assessment, quantitative or qualitative, could be useful in making more cost-effective decisions regarding when to repair. It is also noted that ECA is most beneficial when the vessels are thicker since replacement costs tend to be higher. The majority of vessels in the refinery service are as-welded and less than 38 mm, and replacement costs are relatively low in comparison to those for sophisticated NDE, engineering critical assessment and the overall risk assumed in leaving the damage in.

The remaining three areas, viz., weld repairs, barrier layer, and hydrogen probes, had relatively low average support for further research and development, mainly because of the past experience of the respondents and because their different philosophies to address HIC damage in existing vessels diffuses the focus. Various schools of thought can be summarized as follows:

i) Engineering critical assessment and weld repair of HIC damage have low probabilities of success; therefore focus should be on defining the severity of environment in terms of hydrogen flux through the vessel wall (hydrogen probes) and then taking suitable measures to counter HIC damage; these would be appropriate selection of steels for new construction, use of barrier layers and control of the process itself (inhibitors, etc.) for existing vessels. In this context, a methodology has been proposed (6) to prevent HIC damage in existing equipment wherein the susceptibility to HIC damage is assumed to be primarily a function of the largest inclusion diameter. In this approach, therefore, a threshold hydrogen level is first established experimentally above which hydrogen pressure in the void forming at inclusion can be sufficient to initiate brittle fracture. This threshold level can be translated into hydrogen concentration at the inside surface or the hydrogen flux. Thus, knowing the largest inclusion diameter, one can establish the hydrogen flux at outside surface that must not be exceeded to prevent HIC damage. If hydrogen flux is expected to be higher, then inhibitors, barrier coatings or process stream modifications need to be employed to reduce hydrogen activity at the inside surface. The hydrogen probes can be used in the field as a quality assurance tool to ensure that hydrogen flux is below the calculated value to cause HIC damage.

   Some respondents, however, were not fully aware of the types of hydrogen probes available, and of ease or difficulties in their use.

ii) Once process and vessels have been designed and in-service HIC damage is encountered, it is impractical to modify the process; therefore, barrier coatings are the only effective way to minimize further problems;

iii) barrier coatings, depending on their type (organic, inorganic, liner, etc.), have various drawbacks mentioned earlier (cost, coating break-down and maintainability; inspection difficulties) and therefore effective weld repair procedures must be developed. These would focus on guidelines for baking out procedures, preheat requirements (minimum area that should be preheated), merits of temper bead technique versus postweld heat treatment, approaches to minimize cracking and blister formation during repairs, role of thermal stresses induced during repair, etc.

It should be added in the first two approaches above some qualitative judgement, if not a rigorous ECA is needed before one decides to leave HIC damage in, and to control process or apply a barrier layer to prevent further accumulation of HIC damage during service. The consensus arrived at in the NACE Working Group document (no weld repair of HIC damage) at this time seems to have few adherents in Canada; however, this may change as the draft document is finalized and circulated more widely.

If this view prevails in the future, then management of HIC damage in existing vessels would involve:

i) Establishing a hydrogen flux-steel quality-HIC damage interrelationship; as mentioned before, this is believed to be the objective of an MPC-Industry project nearing completion now;

ii) development of hydrogen probes that can be easily installed, and moved if necessary, to monitor hydrogen flux in service;

iii) if flux is considered to be too high in relation to steel quality, modify process stream environments or apply barrier coating; therefore evaluate pros and cons for various coatings based on process stream environment, temperature, maintainability, etc. and develop quality assurance/specification tests for coatings.

5.0 RECOMMENDATIONS FOR CANMET RESEARCH AND DEVELOPMENT INITIATIVES

It is clear from the background given in Section 4.1 that a considerable number of programs are underway in the U.S.A. that deal with the subject areas of interest to CANMET. It is therefore considered extremely important for CANMET to have representatives involved with key NACE and API Committees, and if possible, have a formal arrangement with MPC for exchange of information.

Secondly, the Canadian industry organizations are not fully aware of the work completed and reported to date at CANMET on subjects such as Cr-Mo weld repair, types and application of hydrogen probes, and these need to be disseminated at the earliest convenient opportunity.

At present, based on the responses received in Canada, the project area that will find greatest support from the petrochemical industry will be in the area of NDE. Such a project can have two objectives:

i) Developing new or enhancing current techniques to improve accuracy in flaw sizing and reducing costs; as a subset, differentiating between HIC damage and inclusion clusters or laminations; such NDE would be effective when performed from the outside surface while the vessel is in operation.

Radiographic techniques based on the tomography principle is one option that needs to be explored for its potential, keeping in mind that the radiography-based technique may not be cost-effective for thick-walled vessels, and equipment will be required to be shut-down.

ii) Developing techniques to non-destructively assess the high temperature microstructural damage and relating it to remaining life. Ultrasonic attenuation is one approach which has been applied for this purpose, however, it is not clear how successful this has been.

Such research can however be considered generic in nature, and may be too commercially oriented for CANMET's mandate.

For high temperature application, two important areas which should find industry support are believed to be:

i) **Relating microstructural damage to remaining life.**

This should initially be carried out in the context of heater tubes made from various alloys and used at different temperatures; a review of the literature to establish the state of the art should be a first step in this direction. The methodologies for ECA in the creep regime should also be included.

ii) **Development of repair welding procedures for Cr-Mo steel.**

CANMET already has an active program in this area, and its output should be circulated to the Canadian refinery and petrochemical industry at the earliest possible (subject to agreement from Ontario Hydro and Novacor - participants in the CANMET program). It is felt that industry would be keen to cooperate in a program focusing on repair of cracks in the overlay and the nozzle areas requiring welding on to Cr-Mo substrate.

In the context of the vessels in sour service, the main questions, beside accurate NDE, relate to **engineering critical assessment of HIC damage and effect of hydrogen on steels fracture toughness**. At the same time, it should be added that the failure of the MEA absorber at the Union Oil refinery in 1984 was caused by a sulphide stress corrosion crack initiating in a hard HAZ. Its subsequent propagation path in the base material was influenced by inclusions but still overall remained perpendicular to the plate surface. This came to be known as SOHIC and was perceived as a major cause of the failure.

To date, no failures seem to have occurred from HIC damage (blisters or step-wise cracking) away from the welds, though vessels have been condemned and retired from service because the HIC damage therein, away from welds, was judged to be too high.

At this time, there are no studies available which would indicate the failure mode for vessels containing HIC damage away from welds. And yet, a subjective 'ECA' is

being performed when some organizations weld repair HIC damage beyond the corrosion allowance.

As discussed earlier, the development of a rigorous ECA methodology for HIC damage seems to be a long term and expensive proposition. However, if the objective is scaled down to demonstrate that HIC damage is not as harmful as planar flaws perpendicular to surface, then that would serve a useful purpose also, as weld repairs or other countermeasures (barrier layer) may not be immediately required. A program focusing on this subject area should therefore involve the following two main components:

i) NDE

Several steel plates containing HIC damage can be procured from retired vessels still with the petrochemical companies; these (selected areas) should be inspected by various existing techniques and then metallographically examined to establish the accuracy of the NDE techniques evaluated in assessing the type and size of the damage.

ii) Fracture Tests

A certain number (4 to 6) of wide plate tests should be carried out on plates having HIC damage as established by an NDE technique selected from those in i) above; the plates could be from retired vessels or flat plates could be artificially charged with hydrogen to produce HIC damage.

The effect of hydrogen on fracture toughness would be established separately, and based on the results, the wide plate tests would be carried out at an appropriate temperature and under hydrogen charging conditions. Perhaps, a single artificially-induced shallow sharp flaw could also be introduced for comparison of its severity in relation to that of the HIC damage.

An alternative, perhaps less expensive, may be to fabricate 4 to 6 small vessels, charge them with hydrogen to produce HIC damage, establish its extent by NDE, and then burst-test them to failure. Such tests can also be modified to sustain hydrogen charging environment under constant pressure to assess flaw growth, hydrogen permeation, etc. Small pressure vessel tests of course better simulate the biaxial loading condition present in service.

Once again, in order to avoid the risk of failure by plastic collapse when only HIC damage is present, it may be prudent to introduce a flaw of known 'low' stress intensity factor so that fracture from this site would be

some indicator of the (low) severity of the HIC damage present in the vessel.

While MPC's program is believed to be following a similar approach of testing pilot scale vessels, the focus therein seems to be planar flaws whereas the program suggested here will focus on HIC damage.

Of the remaining potential areas for research and development, it seems that barrier coatings is an area that may not be well-suited to a CANMET initiative, mainly because it involves evaluation of commercial products, and the evaluation could be dependent on in-service environments, and maintainability considerations which are best carried out at plant scale trials.

The weld repair subject focusing on means to minimize cracking and blister formation, it is suspected, will not find much support.

In **summary**, the recommended area for **CANMET initiatives** therefore are:

i) microstructure degradation-remaining life interrelationship; with a longer term perspective, activity in the area of application of fracture mechanics principles to ECA in the creep range should also be initiated.

ii) repair strategies for 2.25 Cr-1 Mo vessels (nozzle area, cracks in overlay) to avoid postweld heat treatment.

iii) Non-destructive evaluation of, and fracture behaviour due to HIC damage in hydrogen-charged C-Mn pressure vessel steels. (This supplements the current CANMET initiative focusing on engineering critical assessment of planar flaws, perpendicular to plate surface, in hydrogen-charged steels.)

iv) Development of reliable, accurate and cost-effective NDE techniques is an important area deserving attention, if it is within CANMET's mandate.

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APPENDIX A

QUESTIONNAIRE

GENERAL

Pressure vessels subject to hydrogen-related problems have been classified into two groups - those operating at ≤200°C (e.g., fluid catalytic cracking units (FCCU); amine absorber units; sour water strippers, etc. all usually having a wet H_2S environment) and those operating at ≥300°C (hydro processing reactor vessels with high pressure hydrogen environment).

The material damage at low temperatures can take the form of one or more sulphide stress cracking (SSC); stress corrosion cracking (SCC); blistering; hydrogen induced cracking (HIC), stress-oriented hydrogen induced cracking (SOHIC); etc. At high temperatures the hydrogen attack affects the creep behaviour and creep crack growth of the steel. Disbonding of the stainless steel overlay has been another problem observed in some vessels. In both cases, there is concern with the effect of residual hydrogen on the fracture toughness of the steel.

The questions below are divided into two groups, dealing with high temperature and low temperature environments.

PRESSURE VESSELS AND OTHER COMPONENTS OPERATING IN HIGH TEMPERATURE ENVIRONMENTS

1. a) Does your Company operate pressure vessels or other components at high temperature (> 300°C)?

   Yes _____ No _____

   b) Is hydrogen a component of the operating environment also?

   Yes _____ No _____

   c) What are the types of steels that have been used for fabricating the high temperature vessels and components?

   - 2 1/4 Cr-1 Mo _____
   - Mod. 2 1/4 Cr-1 Mo (with V, Ti, etc.) _____
   - 3 Cr-1 Mo _____
   - Others (please specify): _____

   d) Please indicate the thickness range of these components.

   _____ mm to _____ mm

e) Are these components overlayed or clad with stainless steel?

Yes _____ No _____

2. An API Report indicated that ≈ 20 to 25% of Cr-Mo vessels are known to have developed cracks in the wall. In the vessels and components currently in operation in your Company, would you characterize the presence of planar flaws as

Frequent _____ Infrequent _____ Do not know _____

3. (a) Are you satisfied with your ability to detect and size planar flaws in heavy wall vessels?

Technically Yes _____ No _____

Economically Yes _____ No _____

(b) Please indicate the NDE technologies employed.

Wet Fluorescence MPI _____ Advanced Ultrasonic _____

Conventional Ultrasonic _____ Acoustic Emission _____

4. Do you perform an engineering critical assessment before deciding to repair?

For brittle fracture Yes _____ No _____

For creep crack growth Yes _____ No _____

5. Are you satisfied with your weld procedures to repair planar flaws?

Yes _____ No _____

6. In the context of the existing vessels, what subject areas require research, development or review effort? (Please indicate the priorities, 1 being the highest.)

- Effect of hydrogen on creep behaviour _____
- Effect of hydrogen on low temperature toughness _____
- Effect of temper embrittlement on low temperature toughness _____

- Repair of cracks at attachment welds, nozzles, etc. without PWHT _____
- Repair of cracks in overlay without PWHT _____
- Engineering critical assessment methodologies for the high temperature (creep) regime _____
- NDE techniques for sizing flaws _____
- Correlating microstructure to creep damage _____

Other: _____

_____

_____

7. Do you foresee heavy wall Cr-Mo vessels built in the near future in numbers sufficient to warrant a research & development effort to enhance material performance and vessel integrity?

   Yes _____ No _____

8. (a) There is already considerable knowledge of the properties of advanced steels (3 Cr-1 Mo, 2 1/4 Cr-1 Mo-1/4 V etc.). Do you envisage such steels being used for the next pressure vessel fabricated for your Company?

   Yes _____ No _____

   (b) Notwithstanding the work to date, do you think there is a need to characterize further the steel and weldment behaviour in such steels?

   Yes _____ No _____

PRESSURE VESSELS OPERATING AT LOW TEMPERATURES (< 200°C)

9. (a) Do you have a significant number of pressure vessels made from conventional steels operating in a wet H_2S environment?

Yes _____ No _____

(b) Do they have hydrogen damage that needs monitoring and attention?

As welded Yes _____ No _____

Postweld Heat Treated Yes _____ No _____

(c) The steels involved are: A516 _____ A285 _____

A515 _____ Others _____

10. (a) Have you specified and used HIC-resistant steels in the recent past for pressure vessels?

Yes _____ No _____

(b) Has the use of HIC-resistant steels been successful?

Yes _____ No _____ Insufficient service experience _____

(c) Are you satisfied with your current specifications for the HIC-resistant steels?

Yes _____ No _____

11. For new vessels to be fabricated, the preferred approach in countering HIC is to:

Specify HIC-resistant steel _____

PWHT the vessel _____

Both are a must _____

Specify coatings _____

Comments: _____

_____

12. Considering the needs of your Company, the focus for further development work should be on:

Avoiding hydrogen problems in new vessels _____

or

Life enhancement of existing vessels containing H_2 damage _____

13. (a) Since conventional ultrasonic inspection techniques cannot differentiate between inclusion clusters, laminations and HIC, have you tried one or more of the following more sophisticated ultrasonic techniques developed to size HIC damage?

Echographic Ultrasonic Method (Ref. 1) _____

Synthetic Aperture Focusing Technique (SAFT) (Ref. 2) _____

Focused Ultrasonic Scanning Inspection (Ref. 3) _____

Time of Flight Diffraction (TOFD) _____

Holosonic C-Scan Method (Ref. 4) _____

Please briefly indicate your success with the technique(s) tried and limitations (field use, cost).

_____

_____

_____

(b) How important is it to develop/improve the ultrasonic inspection technique for field applications to identify the HIC damage?

Very important _____ Important _____

Desirable _____ Not urgent _____

14. (a) Do you have internal guidelines to perform ECA for HIC damage (blisters and stepwise cracking)?

Yes _____ No _____

(b) If no, would you be in favour of developing such guidelines?

Yes _____ No _____

If no, please expand.

_____

_____

_____

15. (a) Is your current practice to repair the HIC damage (stepwise cracks, blisters) in vessels?

Yes _____ No _____

(b) Are there any major limitations to your current strategy to weld repair HIC damage?

i) No - the procedures are reliable _____

ii) Formation of additional blisters due to preheating and weld repair _____

iii) Other _____

_____

16. Please indicate your priorities for the three most important areas for further development work that would assist you in enhancing the life of the pressure vessels operating at relatively low temperature subject to hydrogen damage.

		Priority
i)	Accurate NDE technique to size HIC damage	_____
ii)	ECA methodology for HIC damage	_____
iii)	Effective weld repair procedures	_____
iv)	Assessing environment severity using H_2 probes	_____

v) Life enhancement by barrier layers (coatings, liners, etc.) _____

vi) Other (please specify): _____

_____

_____

17. Please use the space below to expand on responses to previous questions or for additional comments that can be helpful to CANMET in defining research & development programs that would be of benefit to the industry.

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2. Christensen, C., et al., "Laboratory and In-Service Test Method to Determine Allowable Environment Severity for HIC Containing Vessels in Wet Sour Service (Appendix 2)", report prepared by Force Institutterne, Denmark.

3. Colaiacovo, F., et al. "Ultrasonic Detection of Hydrogen Induced Crack Growth in Pipe Steel", proceedings of 4th European Conference on Non-Destructive Testing, London, U.K., September 1987.

4. Ikeda, A., et al., "Evaluation Method of Hydrogen Induced Cracking Susceptibilities of Steels for Pipeline and Pressure Vessel", International Conference on Interaction of Steel with Hydrogen in Petroleum Industry Pressure Vessel Service, Paris, May 1989.

APPENDIX B

LIST OF QUESTIONNAIRE RECIPIENTS AND RESPONDENTS

QUESTIONNAIRE RECIPIENTS AND RESPONDENTS

NAME	COMPANY	RESPONSE
Mr. T.M. Rogers	Syncrude Canada	Response received
Mr. B. Tkachyk	Suncor Inc.	In-person discussion
Mr. M. Beaton	Petro Canada Products	In-person discussion
Mr. F. Vacha	Shell Canada	In-person discussion
Mr. R.W. MacDonald	Mobil Oil Canada	In-person discussion
Mr. P. Teevens	Amerada-Hess Canada	In-person discussion
Mr. M. Hudson	Fluor Canada Limited	Response received
Mr. J. Anderson	Husky Oil	No response
Mr. D. Pryor	Phillips Petroleum	No response
Mr. D. Helgeland	B.P. Canada	Response received
Mr. L. Lee	Fluor Daniel Inc.	Response received
Mr. J. Wright	Imperial Chemical Industries	In-person discussion
Mr. J. Latuf	BASF Canada Inc.	Telephone conversation
Mr. S. Oliphant	Chevron	No response
Mr. J. Yates	Dupont Canada Inc.	No response
Mr. A. Gysberg	Esso Petroleum Canada	In-person discussion
Dr. S. Lawson	Ontario Hydro Research Division	In-person discussion
Mr. J. Windsor	Irving Oil	No response
Mr. M. Jamieson	Esso Petroleum Canada	Response received
Mr. A. Westelaken	Polysar Rubber Corporation	In-person discussion
Mr. D. Oulton	Novacor Chemicals (Canada) Ltd.	Response received
Mr. E. Sperling	Amoco Corporation	Response received
Mr. O. Draganiuk	Dow Chemical Canada	In-person discussion